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TITLE: A LATTICE FOR A "LOW-FIELD" SUPERCONDUCTING SUPER COLLIDER

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A LATTICE FOR A "LOW-FIELD" SUPERCONDUCTING SUPER COLLIDER*

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Introduction

In this paper I present a simple lattice suitable for a Superconducting Super Collider ("super-super"). This super-super lattice is designed for storage of 20-TeV protons using bending magnets with peak fields of B = 2.1 T. The low-field value is chosen so that the present work may complement presentations of high-field lattices (5 T and 6.5 T)[1,2] given elsewhere at this workshop, and so that this lattice may be used as a working tool to identify field-dependent aspects of the accelerator design.

The super-super design is shown in Fig. 1. I have chosen a "racetrack" design rather than a high-periodicity lattice. The racetrack has two long half-circle arcs connected by two long straight sections. In the initial development of this design, the arcs consist entirely of FODO cells (see the following section); whereas, each straight section contains three "low-beta" sections for high-luminosity interaction regions separated by transport insertions (see "Straight-Section Design"). The transport insertions can be modified easily to include injection, extraction, and rf acceleration devices, as well as other components necessary in a complete super-super design. These refinements will not be developed in this paper.

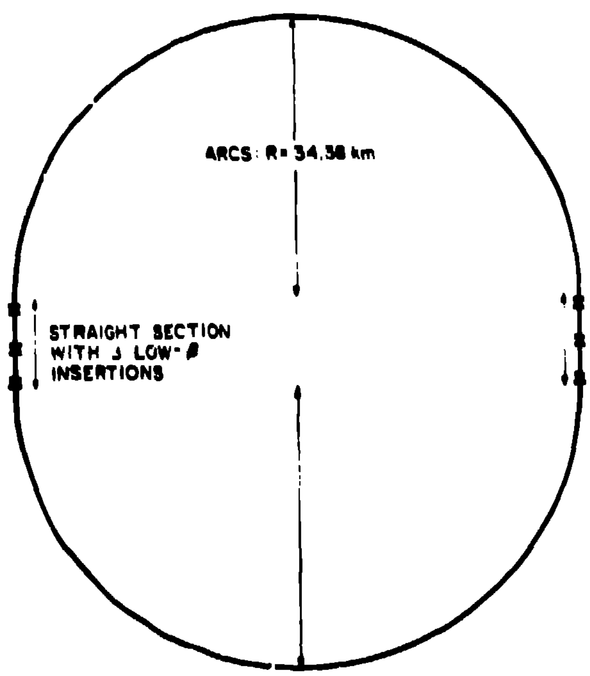

Fig. 1. The super collider ring.

FODO Cell Parameters

The arcs of the super-super are composed of a large number (>500) of FODO cells, which are the basic units of any large alternating-gradient storage ring. A FODO cell is shown in Fig. 2 and consists of a focusing quadrupole and an opposite-strength defocusing quadrupole, separated by long bending magnets. Equations for the Courant-Snyder[3] beam transport parameters β and η are given in Table I for thin lens FODO cells.[4] These equations are accurate in the limit where the quadrupole length is much less than the dipole length, which is true in super-super scenarios.

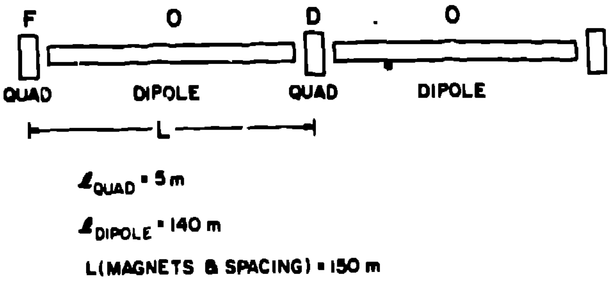

Fig. 2. FODO cell.

Constraints on beam size, determined by the good field apertures of the magnets, limit FODO parameter choices. These constraints are somewhat scenario dependent. If I require that the maximum rms beam size

$$\sigma = \sqrt{\beta_{max}\varepsilon/6\pi}$$

be less than 1 mm at an injection emittance of $0.5 \times 10^{-2}\ \pi$ mm·mrad, I find

$$\beta_{max} < 1200 \text{ m} \quad .$$

From Table I it can be shown that for cells with betatron phase ϕ_0 between 60° and 90°, β_{max} depends only the cell half-length L ($\beta_{max} = 3.3$ L), or L < 350 m.

A second constraint is the requirement that the quadrupole length ℓ_Q be small compared with the cell length. If I require $\ell_Q/L < 0.1$, I find (at $\phi_0 = 60°$)

$$L^2 > \frac{B\rho}{0.1\ B'} \quad .$$

With $B\rho$ = 66 700 Tm for 20-TeV protons and B' = 100 T/m, I find L > 80 m. I choose L = 150 m within these constraints. This cell length choice is relatively independent of maximum bending field B.

The off-momentum function η has a significant dependence on ϕ_0 and on B. From

$$\eta_{max} = \frac{L\theta}{2}\ \frac{2 + \sin(\phi_0/2)}{\sin^2(\phi_0/2)} \quad ,$$

I find η_{max} decreases by a factor of 0.54 as ϕ_0 increases from 60° to 90°. Since off-momentum particle amplitudes are given by $\Delta x = \eta\ \Delta p/p$ this means that the aperture-dependent momentum acceptance is approximately doubled. Similarly, since $\theta \propto B$, momentum acceptance $\propto 1/B$ and the low-field super-super scenario has proportionately greater momentum acceptance. A greater momentum spread may be desirable in avoiding high-frequency coherent instabilities.

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TABLE I
FODO CELL EQUATIONS/PARAMETERS

FODO Cell Elements

Element	Type	Length	Field strength
F	quadrupole	5 m	105.73 T/m
D	quadrupole	5 m	-105.73 T/m
O	dipole	140 m	2.0788 T

Cell Parameters

Parameter	Value
β_{max}	499.20 m
β_{min}	130.45 m
η_{max}	2.449 m
ϕ_o	72°
L	150 m
Θ	0.25°

Thin Lens Equations

$$\beta_{max} = \frac{L}{\sin(\phi_o/2)}\left(\frac{1+\sin(\phi_o/2)}{1-\sin(\phi_o/2)}\right)^{1/2}$$

$$\beta_{min} = \frac{L}{\sin(\phi_o/2)}\left(\frac{1-\sin(\phi_o/2)}{1+\sin(\phi_o/2)}\right)^{1/2}$$

$$\sin\frac{\phi_o}{2} = \frac{pL}{2} \quad \text{with} \quad p = \frac{B_Q' \ell_Q}{B\rho}$$

$$\eta_{max} = \frac{L\Theta}{2\sin^2(\phi_o/2)} \cdot \left[2 + \sin(\phi_o/2)\right]$$

$$\eta_{min} = \frac{L\Theta}{2\sin^2(\phi_o/2)} \cdot \left[2 - \sin(\phi_o/2)\right]$$

$$\Theta = \frac{BL_{dipole}}{B\rho}$$

Optimum cells are chosen with 60° < ϕ < 90°, with the larger ϕ_o permitting greater momentum acceptance at a cost in quadrupole length. The cases with ϕ_o = 60° and ϕ_o = 90° have particularly good symmetry, which makes some design tasks simpler.[1,2] Since an intermediate value may be optimum, and to demonstrate that acceptable designs can be generated for other cases, I choose ϕ_o = 72°, a case with somewhat inferior symmetry (ϕ_o = 2π/5). I anticipate future adjustments as scenario requirements become more definite.

Parameters for this FODO cell are compiled in Table I where thick lenses are used.[3] (ℓ_Q = 5 m and L_o, the dipole length, is 140 m.) With Θ = 0.25° bend per half cell, a field of B = 2.0788 T is required for 20-TeV particles. The momentum aperture under the constraint $\eta\,\Delta p/p$ < 0.001 m is $\Delta p/p$ = ±0.004. Each arc contains 360 FODO cells and together the arcs contribute 216 km to the ring circumference.

TABLE II
LOW-BETA SECTION

Component Label	Type	Length (m)	Field Strength (T/m)
QDA	quadrupole	12.75	-200.1
QFB	quadrupole	22.5	198.4
QDC	quadrupole	12.75	-190.7
L_o	drift	30	

Parameter	Value
β_{min}	2.0 m
β_{max}	2700 m ($\beta_x = \beta_y$)

Straight-Section Design

Each of the two straight sections includes three low-beta sections for high-luminosity collisions. The betatron values at the collision point are chosen to be

$$\beta_x^* = \beta_y^* = 2\text{ m}$$

to comply with currently fashionable super-super parameter choices. Higher luminosity may be obtained using smaller β* (discussed below). The low-beta collision point is surrounded by drift lengths of ±30 m to accommodate detectors. Focusing to obtain small β* is provided by triplets of quadrupoles. (See Fig. 3.) I choose quadrupoles with gradients of ~200 T/m. With apertures of >2 cm, strong fields of >4 T are required. The total length of the triplet is ~45 m. Parameters of the low-beta section are shown in Table II.

An important parameter is β_{max}, the maximum betatron amplitude within the triplet, which determines the required aperture through $\sigma^2 = \beta\,\epsilon^*/6\pi$ where σ is the rms beam size. In Table II β_{max} = 2700 m, which means the beam is magnified by ~2.5 times its size in the periodic lattice.

Lower β* is obtainable by slight modification of the triplet; however, β_{max} is increased following $\beta_{max} \propto 1/\beta^*$. Choosing β* = 0.5 m increases luminosity by a factor of 4 with β_{max} = 11 000 m, doubling the beam size in the triplet. This additional aperture is,

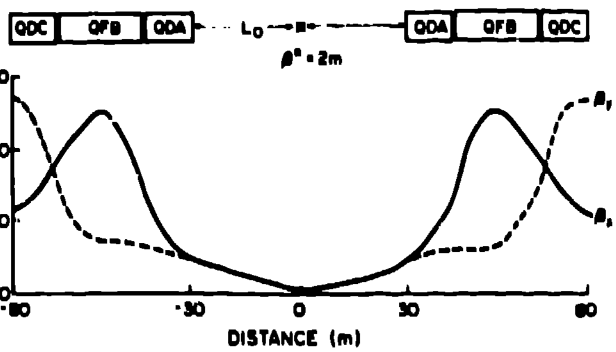

Fig. 3. Low-beta section.

however, probably not difficult to accommodate at 20 TeV for most super-super scenarios; optimization will probably lower β^*. Lower β^* will eventually be limited by the "hourglass" effect: $\beta^* > L_B/2$ with L_B the bunch length.

Matching Constraints

The lattice must include matching of C-S functions[3] between the arcs and the low-beta sections. Figure 4 shows an initial solution to this problem.

The dispersion function in the arc is matched to zero dispersion in the straight sections by "dispersion suppressors"; $\phi_0 = 60°$ and $\phi_0 = 90°$ have particularly simple solutions to this problem. The 60° case is obtained simply by eliminating the bending magnets in the next-to-last FODO cell of the arc. I have chosen to modify this for 72° by varying the drift lengths in this next-to-last cell. The result is drift lengths of 97.12 m and 106.54 m, instead of 145 m, which does perturb β_x, β_y in these last two cells.

Matching of β_x, β_y between the arcs and the triplet is obtained by a weakly defocusing triplet and a long drift space (~500 m). Transport between interaction regions is composed in this initial design of ten 72° FODO cells without bending magnets and triplet/drift sections at the ends of the transport for β_x, β_y matching.

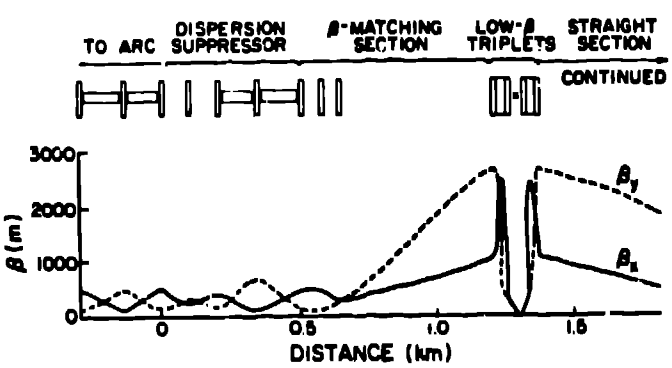

Fig. 4. Matching section.

These low-beta transport-section parameters are easily readjusted to obtain $\beta^* = 1$ m.

The solution displayed here is symmetric about the low-beta point and can be directly implemented in a $p\bar{p}$ collider or a pp collider in which the beams are separated in separate final-focusing triplets. If opposing proton beams pass through the same triplets, they see opposite polarities and, therefore, different matching conditions that can be met by weakly defocusing quadruplets. An antisymmetric solution may be preferred, and has been generated. Overall lattice parameters and beam dynamics do not differ significantly.

Summary of Lattice Properties

In Table III the lattice parameters are displayed, and the complete lattice structure is outlined.

TABLE III
SUMMARY OF PARAMETERS

Lattice Parameters

Parameter	Value
Circumference	238 km
Tunes	$\nu_x = 158.315$
	$\nu_y = 158.163$
β^* -- low beta value	2.0 m
β_{max} -- largest beta value	2700 m
FODO period length	300 m
ϕ_0 phase advance/cell	72°
Natural chromaticity	$\xi_x = -1.468$
$\xi = \Delta\nu/\nu \;/\; \Delta p/p$	$\xi_y = -1.389$
Transition energy	$\gamma_t = 155.4$

Lattice Structure of One-fourth Ring

Elements	Length (km)
Arcs: 179 FODO cells	53.7
Dispersion suppressor	0.51116
Match to 1st low beta	0.78884
Low beta to straight-section transport	0.75
Straight section (4π phase advance)	3.0
Straight section to central low beta	0.75

Correction elements are not yet included; however, the linear chromaticity can be easily corrected by insertion of two families of sextupoles in the FODO cells. The lattice will be studied using particle-tracking codes to determine the effects of higher order chromaticity, chromatic aberrations in the low-beta optics, and sensitivity to magnet errors, and to design necessary correction systems.

Acknowledgments

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